

# REPORT DOCUMENTATION PAGE

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## 14. ABSTRACT

The aim of this project was to demonstrate the electrical gating of the magnetic response in magnetically-doped semiconductor nanostructures. The PI at Penn State (Samarth) developed a variety of different materials for this purpose using molecular beam epitaxy, and then worked in a close collaborative effort with the PI at Stanford (Goldhaber-Gordon) on magneto-transport measurements of these systems. The principal result was the demonstration of a new phenomenon: an electrically-tunable anomalous Hall effect in magnetically-doped two-dimensional electron gases.

## 15. SUBJECT TERMS

Magnetic semiconductor, nanostructure, two-dimensional electron gas

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## Final Technical Report: Electrically-gated ferromagnetism in semiconductor nanostructures

Investigators:

Prof. Nitin Samarth (PSU): ONR N00014-02-1-0996

(Note: this grant was funded as a collaborative project with Prof. David Goldhaber-Gordon at Stanford University, Prof. C. M. Marcus at Harvard and Prof. A. Kent at New York University.)

Period of performance: 9/1/2002 - 8/31/2005

### Summary of technical accomplishments

The aim of this project was to engineer semiconductor nanostructure geometries wherein one can electrically manipulate the magnetic behavior of a material. At Penn State University, our goal was to fabricate magnetically-doped semiconductor heterostructures that would be employed in magneto-transport experiments by our collaborators at Stanford, Harvard and NYU. We fabricated the following classes of materials for this project:

- **Magnetically-doped two dimensional electron gases** derived from ZnSe; these samples were developed in close collaboration with Prof. Goldhaber-Gordon at Stanford. A systematic effort was implemented for electrical gating of these 2D systems with the eventual aim of making quantum dots. Although the gating scheme developed in this project was a great improvement over existing methods, it was not robust enough for making high quality quantum dot samples. We speculate that the principal obstacle to robust gating in this material stems from the presence of deep traps that result in hysteresis effects and screening, complicating the reproducible depletion of regions for quantum dot formation. Nonetheless, the project resulted in an interesting discovery: we found that quantum transport studies of electrically-gated magnetic 2DEGs showed clear evidence of an anomalous Hall effect arising from spin-dependent scattering. This is an unexpected result given the weak spin-orbit coupling in these samples, and raises unresolved questions about the origins of the anomalous Hall effect in disordered systems (these 2DEGs have a mobility typically around  $0.5 \text{ m}^2/\text{V.s}$ ). The discovery was published in *Physical Review Letters* [1]. Our discovery of the anomalous Hall effect in these systems has attracted significant interest in the condensed matter physics community, with invited talks at the 2007 March Meeting of the American Physical Society in Denver, the 2006 Spintronics Program at the Kavli Institute at UC-Santa Barbara, and the 2007 Joint MMM/Intermag conference in Baltimore. Senior personnel on this project also gave invited seminars on this work at prominent universities (Princeton, Ohio State, Michigan State, Rochester).

- **Magnetically-doped GaAs heterostructures** were developed for patterning into mesoscopic patterns that would be measured in collaborative efforts with Prof. Marcus at Harvard. The essential idea was to fabricate nanoconstructions wherein the local carrier could be electrically controlled, hence altering the ferromagnetic state. Although a variety of protocols were developed for nanopatterning of the material (see figure below), difficulties with the processing of devices incorporating gates prevented successful completion of this project.

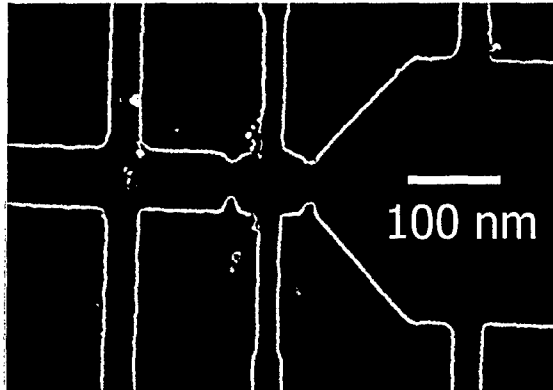


Fig. 1. Submicron (Ga,Mn)As device with nanoconstrictions

### References

1. J. Cumings, J., L.S.Moore, H.T.Chou, K.C.Ku, G.Xiang, S.A.Crooker, N.Samarth, D.Goldhaber-Gordon, "A Tunable Anomalous Hall Effect in a Non-ferromagnetic System," Phys. Rev. Lett. **96**, art. No 196404 (2006).

### Invited Talks on Project Results

- January 2006, "Spin Control in Ferromagnetic Semiconductor Heterostructures." California Nanosystems Institute Seminar, University of California-Santa Barbara CA.
- February 2006, "Spin Control in Ferromagnetic Semiconductor Heterostructures." Condensed Matter Physics Seminar, Ohio State University, Columbus OH.
- March 2006, "Spin Transport in Magnetic Semiconductor Heterostructures," Kavli Institute of Physics Spintronics Conference, University of California, Santa Barbara CA.
- April 2006, "Spin Control in Semiconductor Quantum Structures" Physics Colloquium, Texas A&M University, College Station TX.

- May 2006, "Spin Transport in Magnetic Semiconductor Heterostructures," Workshop on Strongly Correlated Electron Systems, Seillac, France (declined).
- June 2006, , "Spin Transport and Scattering in Magnetic Semiconductor Heterostructures," "Experimenter of the week" Seminar, Program on Spintronics, Kavli Institute for Theoretical Physics, University of California-Santa Barbara CA.
- June 2006, "Spin Transport in Magnetic Semiconductor Heterostructures," US-France Workshop on Spintronics, Grenoble, France (declined).
- October 2006, "The spin and anomalous Hall effects in surprising places," Condensed matter physics seminar, Princeton University, Princeton NJ.
- November 2006, "The spin and anomalous Hall effects in surprising places," Condensed matter physics seminar, Ohio State University, Columbus OH.
- November 2006, , "The spin and anomalous Hall effects in surprising places," Condensed matter physics seminar, University of Rochester, Rochester NY.
- January 2007, "Spin Transport and Scattering in Magnetic Semiconductor Heterostructures," 10<sup>th</sup> Joint Magnetism and Magnetic Materials/Intermag Conference, Baltimore MD.
- March 2007, "Spin Transport and Scattering in Magnetic Semiconductor Heterostructures," March Meeting of the American Physical Society Denver CO.



October 6, 2006

Dr. Chagaan Baatar  
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Ballston Centre Tower One  
800 North Quincy Street  
Arlington, VA 22217-5660

Re: N00014-02-1-0996 Final Report

Dear Dr. Baatar:

Enclosed please find the Final Technical Report for the subject grant. Please contact me if you require further information.

Sincerely,



Denise M. Hlivia  
Asst. Coordinator, Contracts & Grants Mgmt.

Cc: R. Baerga via email  
Defense Technical Information Center  
Naval Research Laboratory  
N. Samarth via email  
D. Shaw via email